

Interface Finite Elements for the Analysis of Fracture Initiation and Progression

Final Report – Summary of Research

**Eric R. Johnson
Principal Investigator**

Performance Period: 15 May 2000 to 14 May 2003

NASA Cooperative Agreement NCC-1-398

**Aerospace and Ocean Engineering Department
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061-0203**

June 2, 2003

Technical Officer: Dr. Damodar R. Ambur, Mail Stop 188-E
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23681-2199

Interface Finite Elements for the Analysis of Fracture Initiation and Progression

Eric R. Johnson
Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0203

Introduction

Progressive failure analyses (PFA) are important for the prediction of residual strength and damage tolerance of vehicle structures, and to predict the energy absorbing capability of vehicle structures under crash-type loads. Typically continuum damage mechanics (CDM) and fracture mechanics (FM) are the methods used for PFA. The method of interfacial damage mechanics (IDM) is used for PFA in this research. IDM has capabilities intermediate between CDM and FM, and is used to numerically model the initiation, growth, and arrest of cracks. IDM smooths the stress singularity at the crack tip, and is easily adaptable with other nonlinearities such as plasticity and material damage. IDM is implemented by user-defined interface elements in the ABAQUS/Standard structural analysis software package. The structural components selected to demonstrate the effectiveness PFA using interface elements are, for the most part, those with published test data. These structural components were subjected to quasi-static loading in the tests. Thus, the ABAQUS analyses are used to predict geometrically and materially nonlinear equilibrium states. Impact loading, dynamic fracture, reflected stress waves, inertia, and time dependent material behavior are not considered.

Interface element

In traditional fracture mechanics an initial crack and self-similar progression of cracks are assumed. Using IDM as implemented with interface finite elements, it is possible to predict non-self-similar progression of cracks without specifying an initial crack. A cohesive-decohesive zone model, similar to the cohesive zone model known in fracture mechanics as Dugdale-Barenblatt model, is adopted to represent the degradation of the material ahead of the crack tip. This model unifies strength-based crack initiation and fracture based crack progression.

The cohesive-decohesive zone model is implemented as an idealized interfacial surface material that consists of an upper and lower surface connected by a continuous distribution of disconnected normal and tangential springs that obey a nonlinear law. The springs act to resist either Mode I opening, Mode II sliding, Mode III sliding, or mixed mode. The initiation of fracture is determined by the interfacial strengths, and the progression of fracture is determined by the critical energy release rates. The idealized interfacial surface material is positioned between two adjacent laminae of a laminated composite structure, or between the adherend and the adhesive of a bonded joint, to predict interfacial fracture. The interfacial surface material is positioned within the bulk material to predict discrete cohesive cracks.

The principle of virtual work is used to formulate the interface element, where cohesive-decohesive tractions are work-conjugate to the displacement jumps across the upper and lower surfaces of the element. The formulation accounts for finite displacements and rotation of the upper and lower surfaces. Various mechanical softening constitutive laws, thermodynamically consistent with damage mechanics, are postulated that relate the interfacial tractions to the components of the displacement jump. An exponential function is used for the constitutive law such that it satisfies a multi-axial stress criterion for the onset of failure, and satisfies a mixed mode fracture criterion for the progression of cracks. A damage parameter is included to prevent the restoration of the previous cohesive state between the interfacial surfaces. Interpenetration of cracks faces is naturally resisted by the development of compressive tractions. A contact friction model based on a modified Coulomb law has been implemented to resist sliding of closed crack faces. Also, the interfacial constitutive law is extended to include subcritical crack growth under cyclic fatigue loading. Line interface elements are developed for use in plain strain models, and surface interface elements are developed for use in three dimensional structural models.

Summary of results

Reference [1] in the section Publications Originating from Grant Research on page 5 is a dissertation detailing all the research performed under this grant, and, in particular, contains those topics either not fully covered in Refs. [2-7] or not reported in the open literature at the time of writing this report.

Reference [2] presents results on computational issues for Mode I loading of the double cantilever beam configuration. Issues studied include mesh sensitivity, the number of integration points, the integration scheme, the mathematical form of the softening constitutive law, and the convergence characteristics of the nonlinear solution procedure when using cohesive-decohesive constitutive laws. To achieve good numerical convergence performance, the interface elements ahead of the crack tip must have integration points within the softening portion of the interface constitutive law. Increasing the mesh density is one way to have elements with integration points in the softening region of the constitutive law. If the mesh density is sufficiently refined, then increasing the number of integration points in the element is another way to achieve more integration points in the softening region. The length of the process zone ahead of the propagating crack in the double cantilever beam configuration was determined for the bilinear, polynomial, and exponential forms of the constitutive law. Knowing the process zone length for a propagating crack is important for determining the element size to achieve good convergence performance. There are large stress gradients in the interface elements ahead of the crack tip, and when using the bilinear law it is known that oscillatory interfacial traction distributions occur for Gauss integration, but Newton Cotes integration results in smooth distributions. It is shown in Ref. [1] that the exponential law results in smooth distribution of the interfacial tractions using either the Gauss or the Newton Cotes numerical integration schemes. Also, when using Newton's method for nonlinear solutions, the exponential law performed better than the bilinear law in convergence studies since the tangent stiffness matrix is smooth for the exponential law but discontinuous in the for the bilinear law [2].

Reference [3] presents the extension of the formulation of the interfacial constitutive law of Ref. [2] to predict the initiation of delamination governed by a multi-axial interlaminar stress criterion, and to predict the progression of delamination cracks based on an empirical mixed mode fracture criterion. A damage parameter is included in the formulation to prevent the restoration of the previous cohesive state. Features of this interface constitutive law are demonstrated for loading and unloading of the double cantilever beam configuration, the end load split configuration, the end notch flexure configuration, and the fixed ratio mixed mode configuration. The finite element results are in excellent agreement with the analytical solutions available in the literature and those independently developed in this research.

Reference [4] presents the results of PFA of a laminate composite square plate subjected to in-plane shear and two laminate composite circular cylindrical panels subjected to axial compression. These panels contained central circular cutouts and experimental results were reported in previous studies. The test data suggested a sequence of intralaminar and interlaminar failures occurring during the postbuckling response of the panels. Intralaminar failure was modeled by a matrix-cracking mode, a fiber-matrix shear mode, and a fiber failure mode. Subsequent material degradation is modeled using damage parameters for each mode to selectively reduce lamina material properties. The interlaminar failure mechanism of delamination is simulated by positioning interface elements between adjacent sublaminae. For the shear panel and the compression panels, the PFA predicted that intralaminar damage induces delamination at the free edge of the cutout at the same locations identified in the experiments. Delamination growth occurred perpendicular the loading direction in regions where large compression loads are present. As the shear panel collapsed, a rapid progression of delamination perpendicular to the loading axis was predicted, while delamination arrest was predicted parallel to the loading axis. Delamination growth occurred perpendicular to the compression axis for the two curved panels with different cutout diameters. The compression panel with the smaller cutout failed with a rapid progression of delamination from the free edge of the cutout. For the compression panel with the larger cutout, delamination growth was followed by arrest. Following delamination arrest, the compressive load stopped decreasing with increasing shortening consistent with the test. Further increases in the shortening precipitated a second delamination growth and led to collapse. Very good agreement between the progressive failure analysis and the experiments is achieved if the PFA analyses includes the interaction of intralaminar and interlaminar failures in the postbuckling response of the panels.

References [5] and [6] present results on the PFA of adhesively bonded joints using interface elements. Joint geometries considered were the single lap, double cantilever beam, and crack lap shear. Analyses were compared to test data for these configurations. The interfacial constitutive law was modified to include different exponents for the individual modes in the mixed mode fracture criterion. For the single lap shear specimen, interfacial cracks between the adhesive and adherend initiated at the reentrant corners and propagated to the center of the overlap, which is consistent with the test. Excellent agreement between the analysis and test was achieved on the load-displacement plot. For the double cantilever beam, the analysis agreed very well with the test on the plot of load versus tip deflection. The predicted oscillatory characteristics of the crack path are consistent with the experimental findings. For the crack lap shear configuration, the analysis predicted initiation of a crack at the reentrant corner between the strap and the adhesive. In addition, the location of crack initiation and its subsequent trajectory was shown to depend on the

relative maximum strengths of the interface and the adhesive. If the adhesive strength is greater than the interfacial strength, then the crack initiates at the interface. If the adhesive strength is less than the interfacial strength, then the crack initiates cohesively. The analysis predicted the shape of a crack at the reentrant corner to be very similar to the shape observed in the test.

Reference [7] documents the extension of the interfacial constitutive law to account for fatigue damage accumulation as a function of the maximum and minimum effective displacement jumps. Damage accumulates not only along the softening path of the constitutive law but also along an unloading path, enabling the simulation of subcritical crack growth with energy dissipation less than the fracture toughness. With this extension, the fatigue crack growth of the adhesively bonded, double cantilever beam configuration was predicted. The load was applied cyclically with constant amplitude and crack growth was monitored throughout the analysis. It is demonstrated that the plot of the cyclic crack growth rate versus the range in the applied stress intensity factor emerges naturally from the numerical analysis including the threshold and Paris law regimes. There were no experimental data available for this configuration. Hence, the paper serves to show that the extension of the interfacial constitutive law to fatigue has qualitatively the correct characteristics.

Student Supported by the Grant

Vinay K. Goyal, Doctor of Philosophy in Aerospace Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061, December 2002.

Publications Originating from Grant Research

(Speaker indicated by the asterisk, if a conference presentation was given.)

- [1] Goyal, Vinay K., Analytical Modeling of the Mechanics of Nucleation and Growth of Cracks, Doctoral Dissertation, Aerospace Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061, December 2002. (This dissertation was also published as a report and given to the NASA technical officer.)
- [2] Goyal-Singhal*, V. K., and Johnson, E.R., Computational Issues in Modeling the Delamination Process Using Interface Elements, *Proceedings of the American Society for Composites, 16th Technical Conference, on Disc [CD-ROM]*, Edited by M.W. Hyer and A.C. Loos, CRC Press LLC, Boca Raton, FL, 2001 (9-12 September 2001, Virginia Tech, Blacksburg, VA).
- [3] Goyal*, V., Johnson, E.R., D vila, C., and Jaunky, N., An Irreversible Constitutive Law for Modeling the Delamination Process Using Interface Elements, *43rd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics, and Materials Conference Proceedings on Disc [CD-ROM]*, American Institute of Aeronautics and Astronautics, Reston, VA, 2002, AIAA Paper No. 2002-1576.
- [4] Goyal*, V.K., Jaunky, N., Johnson, E.R., and Ambur, D., Intralaminar and Interlaminar Progressive Failure Analysis of Composite Panels with Circular Cutouts, *43rd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics, and Materials Conference Proceedings on Disc [CD-ROM]*, American Institute of Aeronautics and Astronautics (AIAA), Reston, VA, 2002, AIAA Paper No. 2002-1745.
Also to appear in the **Journal of Composite Structures**; accepted May 15, 2003.
- [5] Vinay K. Goyal* and Eric R. Johnson, Analysis of Initiation and Progression of Cracks in Adhesive Joints, Center of Adhesive and Sealant Science, MACRO 2002: An Update of Macromolecular Education and Research at Virginia Tech, September 4-6, 2002, Blacksburg, Virginia. (Presentation only.)
- [6] Goyal*, V.K., Johnson, E.R., and Cassino, C., Computational Model for Progressive Failure of Adhesively Bonded Joints, The *44th AIAA/ASME/ASCE/ASC Structures, Structural Dynamics, and Materials Conference Proceedings on Disc [CD-ROM]*, (Norfolk VA 7-10 April 2003), American Institute of Aeronautics and Astronautics (AIAA), Reston, VA, 2003. (Paper Number AIAA-2003-1597)
- [7] Goyal*, V.K., and Johnson, E.R., Cohesive-Decohesive Interfacial Constitutive Law for the Analysis of Fatigue Crack Initiation and Growth, The *44th AIAA/ASME/ASCE/ASC Structures, Structural Dynamics, and Materials Conference Proceedings on Disc [CD-ROM]*, (Norfolk VA 7-10 April 2003), American Institute of Aeronautics and Astronautics (AIAA), Reston, VA, 2003. (Paper Number AIAA-2003-1678).